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LLM: An L-Band Multibeam Land Mobile Payload for Europe

J.Benedicto , E.Rammos
G.Oppenhaeuser , A.Roederer
European Space Agency
P.O.box 299, 2202 AG Noordwijk, The Netherlands
Phone:31-01719-83944 Fax:31-01719-84596

1 Abstract

The European Space Agency is developing, in the frame of the ARTEMIS programme, a multibeam reconfigurable mobile payload to provide pre-operational land-mobile satellite services at L-band over Europe .

The LLM payload features high capacity at L-band, efficient use of the L-band spectrum resources and flexibility in reconfiguring the allocation of bandwidth and RF power resources to the different beams. Additionally, a number of features have been added to the payload purely for experimental purposes, like the provision of one steerable spot beam which can be repositioned anywhere within the coverage area, and the possibility to reuse L-band frequencies by spatial discrimination between non-adjacent beams, or via orthogonal polarisations.

This paper describes the architecture of the payload, and the hardware implementation of the most critical subsystems.

2 Introduction

The expansion of the Mobile Satellite Service to new emerging communities of users (in particular land-based mobiles and aircrafts) is very much dependent upon the additional capacity and flexibility that the space segment can bring into the system. This leads to specific payload requirements, like the need to generate multiple high-gain spot beams over the service area, to provide adequate beam-to-beam interconnectivity with efficient means of reconfiguring the allocation of on-board power and spectrum resources between the different beams to minimise the system blocking probability. Moreover, the limitation of the L-band spectrum resources suggests the need for frequency reuse which can be provided by spatial or polarisation discrimination.

An L-band Land-Mobile (LLM) payload has been designed to meet the above system requirements and to establish a payload architecture concept with growth capability, such that it could be expanded, in a second generation LLM, to increase further the L-band EIRP and the frequency reuse capability.

3 Payload performance

The main payload performance parameters are summarised in this section.

FREQUENCY PLAN: The signals to and from the mobiles are relayed by the satellite at L-band in the 1.6/1.5 GHz frequency bands (Mobile Link), and the feeder link with the Base and Gateway fixed stations is established at Ku-band, in the 14/12 GHz frequency bands.

The L-band frequency plan follows the WARC-MOB'87 allocation (Fig-1). The LLM payload subdivides the L-band spectrum into three functional bands:

- L1: 1530-1533 MHz for telephony/data traffic to land-mobiles through spot beams (3 MHz)
- L2: 1555-1559 MHz for telephony/data traffic to land-mobiles through spot beams (4 MHz)
- G: a slot of 4 MHz contained anywhere between 1533-1555 MHz for low data rate traffic to land-mobiles through a global Eurobeam

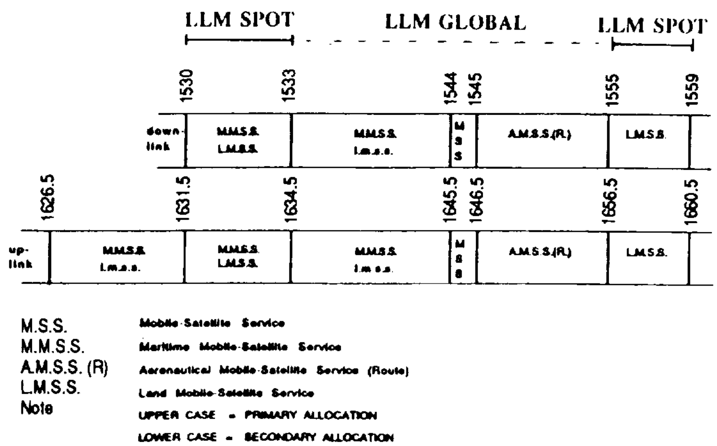

Fig.1: MSS WARC-MOB'87 frequency allocation

The bands L1 and L2 are combined together in the Feeder Link into the "M" type of channels. Channels M1, M2 and M3 reproduce the same part of the L-band spectrum in order to allow frequency reuse by spatial isolation and/or polarisation discrimination, and to cater for redundancy within the "M" type of filter banks. In summary the LLM payload covers 7 MHz (3+4) allocated on a primary basis to the Land-Mobile Satellite Service (LMSS), and 4 MHz from the band allocated to LMSS on a secondary basis and to AMSS (aeronautical) on a primary basis.

At Ku-band four non-adjacent channels are used. Three of them, M1, M2 and M3 are 8.5 MHz wide whereas the fourth, G, covers 4 MHz. The "M" channels provide 7 MHz of useful bandwidth in 1 MHz slots, and additional 250 KHz slots to cater for the guardbands of the IF Processor SAW filters (Fig-2). The channels are distributed across the 14.0-14.5 GHz band in the up-link and 11.45-11.70 GHz and 12.50-12.75 GHz in the down-link. The exact location of the channels is not defined yet, and will be coordinated with Ku-band european operators, in particular EUTELSAT.

SPECTRUM HANDLING EFFICIENCY: One of the most important features of the IF Processor presented in section 4 is its high efficiency in handling the L-band spectrum. The use of offset frequency conversions for adjacent frequency slots (Fig-2) eliminates the loss of spectrum due to filter guardbands, eases at the same time the out-of-band rejection requirements for the SAW filters, and reduces the coherent multipath component through the repeater.

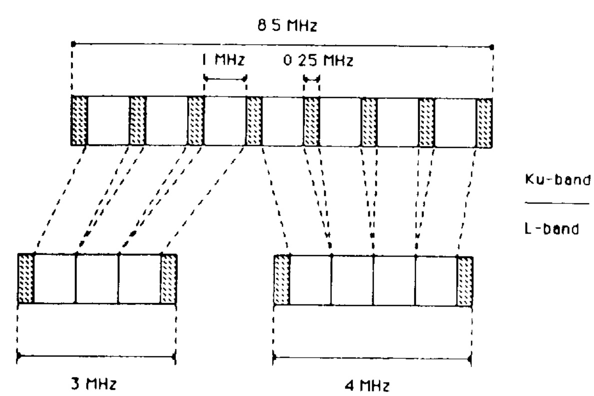

Fig.2: LLM channelisation plan

COVERAGE: The LLM payload covers all Western Europe, the upper North Africa and part of the Middle East. The coverage is provided, at L-band, in three complementary ways:

- with a single Eurobeam (Fig-3)
- with a set of six fixed spot beams (Fig-4)
- with a steerable beam which can be repositioned anywhere within the coverage area with a resolution of one degree.

One additional fixed spot beam is generated in opposite circular polarisation (RHCP), overlapped with one of the LHCP beams, in order to carry out experiments of frequency reuse by polarisation discrimination in CDMA and FDMA systems.

The total number of beams that the payload can generate at any one time is 9. Two additional steerable beams are implemented onboard for redundancy purposes.

The same coverage is implemented in the Forward and the Return links.

The coverage at Ku-band is equivalent to the L-band Eurobeam.

EIRP AND G/T: The payload exhibits the following EIRP and G/T performance:

coverage	EIRP	G/T
L-band spot	51 dBW	+2.5 dB/K
L-band Eurobeam	45 dBW	-2.0 dB/K
Ku-band Eurobeam	38 dBW	-2.0 dB/K

The available RF power resources can be shared in any ratio among the Eurobeam and any of the fixed or steerable spot beams at L-band, in order to match the non-uniform distribution of the traffic across the coverage area.

The L-band EIRP requirements have been sized with the intention to provide a good balance between RF power and spectrum availability. The capacity of the payload in terms of communication channels is approximately 1000 voice channels of 4.8 Kbps data rate (R3/4 Viterbi encoding), QPSK modulated with a channel spacing of 10 KHz.

BEAM-TO-BEAM ISOLATION: The L-band spot beam coverage of Europe (Fig-4) is such that 15 to 20 dB of isolation are provided between the NW and SE beams and between the SW and the two most SE beams. This feature will be used to perform experiments of frequency reuse by spatial discrimination in FDMA and CDMA systems.

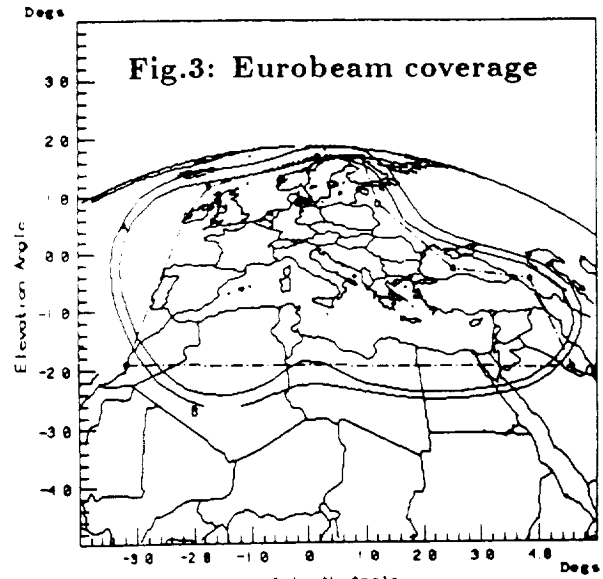

Fig.3: Eurobeam coverage

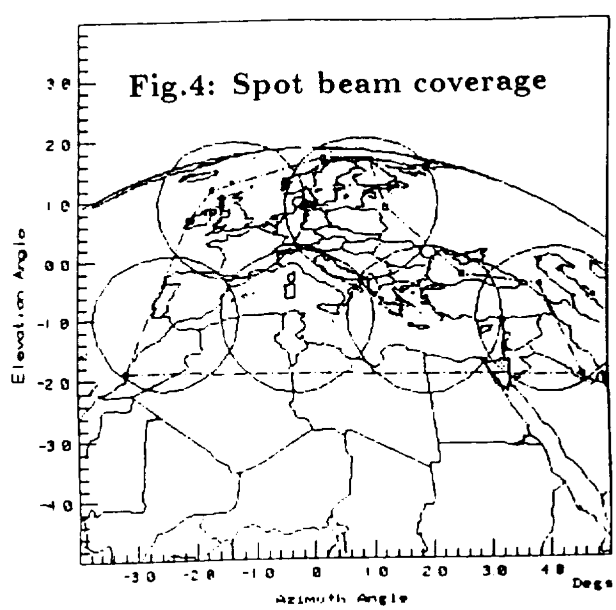

Fig.4: Spot beam coverage

IN-ORBIT RECONFIGURABILITY: The LLM payload exhibits a high degree of in-orbit reconfigurability to ease the operation of the spacecraft, and to optimise, at any time, the use of the on-board resources to maximise the system capacity. The reconfiguration of the payload can be implemented at different levels:

- flexible allocation of the L-band spectrum resources to any of the spot beams or the Eurobeam.
- flexible share of the generated L-band RF power (120 Watts) among the different beams, to match the variable assignation of bandwidth per beam. This variable power sharing capability is implemented with no loss in TPA power efficiency.
- the provision of a steerable spot beam to cope with seasonal or diurnal peak traffic distributions without the need to reconfigure the capacity allocated to any of the remaining fixed beams.
- the flexibility in the positioning of the G channel, intended to ease the tasks of coordination with other systems and to make a provision for an eventual future increase (in WARC-MOB'92) of the bandwidth allocated to the LMSS service.

4 Payload description

GENERAL: A block diagram of the LLM payload is given for illustration in Fig-5. The payload consists of the Forward and Return transponders. The Forward (FWD) transponder receives the signals from the fixed earth stations at Ku-band and relays them to the mobiles at L-band. The Return (RTN) transponder does the reverse operation.

In the Forward transponder, the Ku-band receiver amplifies and down-converts the signals from Ku-band to L-band (1950-1979 MHz) and feeds them into the IF Processor. The FWD IF Processor (IFP) operates with L-band input and output interface frequencies. It is responsible for the routing of signals through the payload. Channel filtering is implemented using SAW filter technology , and channel-to-beam switching is realised with L-band MMIC multithrow switches. The output of the IFP is a set of 11 beam drive signals (nine active beams and two redundancy ones) at L-band (1530-1559 MHz). The L-band TX front end uses a novel multimatrix antenna feed system with overlapped beam feed clusters [1] which consists of a low power Beam Forming Network (BFN) , a set of twelve cold-redundant 10 Watt transistor power amplifiers (operating at 16 dB of noise power ratio), and a set of three 4x4 Butler-like hybrid matrices, which steer the amplified beam drive signals to the corresponding antenna feed elements. The L-band antenna is common for TX and RX, and consists of a large unfurlable reflector (5x5.6 meter projected aperture) fed from its focus by an array of twelve feeds. Each of the twelve antenna feed elements is equipped with an L-band diplexer, and in addition three of them with an orthomode transducer to provide dual circular polarisation for one beam.

The signals received by the L-band antenna are amplified by 15 LNAs which are connected to the L-band diplexers. The RX beams are configured by a passive RTN Combiner which performs the opposite of the combined function of the FWD low-power BFN and Butler-like matrices . The RTN IFP performs a function equivalent to the FWD IFP. The only difference is in the degree of channelisation of the G channel, which is increased to 1 MHz (as opposed to 4 MHz in the FWD) to protect the transponder against interference from systems using the same frequency band. The L-band output signals of the RTN IFP are up-converted to Ku-band by the RTN Up-Converter which drives a

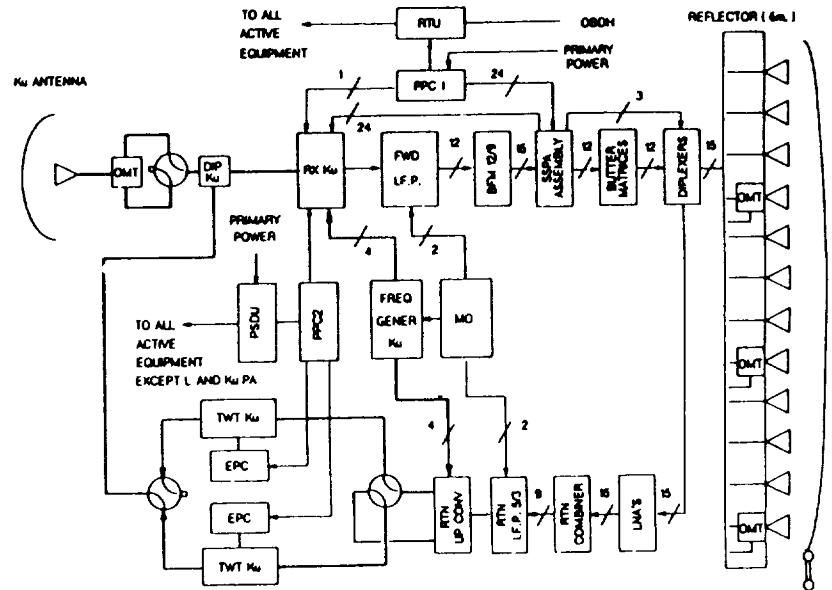

Fig.5: LLM Payload block diagram

cold-redundant Ku-band High Power Amplifier providing 20 Watts of useful output power at 21 dB of noise power ratio. The Ku-band antenna is a center-fed reflector antenna of 450 mm diameter, which is common for TX and RX.

The most characteristic subsytems of the LLM payload are the IF Processor (including Frequency Generation equipment), and the L-band Transmit and Antenna subsystems. Those are described in detail herebelow:

IF PROCESSOR: The IFP performs the onboard routing of the signals to and from the different beams. It is therefore responsible for providing an adequate interface between the Feeder Link and Mobile Link frequency plans, to handle efficiently the spectrum resources, and to provide the beam-to-beam interconnectivity paths through the payload.

The IFP contains a bank of SAW filters operating in the range 140 to 169 MHz which cover the channels M1,M2, M3 and G . The filters provide more than 37 dB of out-of-band rejection at 250 KHz away from the passband. The filter bandwidths are of 1 MHz for the filters contained in channels M1, M2 and M3 and 4 MHz for channel G. All filters are manufactured on quartz substrate in order to achieve good temperature stability. Each of the filter outputs, upconverted to L-band, can be routed to any of the 11 input ports of the BFN by the use of miniaturised MMIC multithrow switches which provide over 40 dB isolation.

In order to maximise the efficiency in handling the L-band spectrum, a novel technique of filter guardband reduction has been implemented. It consists of compressing (or expanding in the RTN transponder) the seven 1 MHz slots contained in a 8.5 MHz-wide "M" channel down to contiguous 3 and 4 MHz bands (L1 and L2) as shown in Fig-2. Each 1 MHz slot at IF is up-converted by a different local oscillator signal. Adjacent local oscillator signals are offset by an amount equal to the filter transition band (250 MHz). In this way 100 per cent spectrum efficiency is obtained at L-band.

The frequency overlapping at L-band of the channels M1, M2 and M3 would allow reusing the same frequencies in three beams at the same time. Moreover, since each of the 1 MHz frequency slots is controlled in frequency by a different frequency synthesizer of 250 KHz resolution, up to six slots can be overlapped in frequency to provide six-fold frequency reuse, or the use of the same band in all spot beams, for a multibeam CDMA system.

The implementation of such an IF Processor is largely dependent upon the use of miniaturised frequency synthesizers. Seven such synthesizers are needed for the LLM IF Processor, the outputs of which are reused by the FWD and RTN transponders. Each synthesizer features 250 KHz resolution and 25 MHz bandwidth in the L-band frequency range (1500 MHz), with outstanding phase noise and spurious performance. The mass of each unit is 150 grams, and the power consumption 2.5 Watts.

L-BAND TRANSMIT AND ANTENNA SUBSYSTEMS: The L-band antenna has to provide simultaneously one Eurobeam, a set of six fixed spot beams and one steerable spot beam, as indicated before. In order to meet the EIRP requirements, the Eurobeam edge-of-coverage directivity has to be around 27.5 dBi (Fig-3) and the spot beam directivity around 33.5 dBi (fig-4). In addition to that, RHCP has to be provided in one of the spot beams for experimental purposes. However, the requirements which have driven to a large extent the design of the L-band antenna are the beam-to-beam isolation for frequency reuse and the need to have flexibility in RF power to beam allocation in order to cope with fluctuations of the traffic across the coverage area.

In view of the above requirements, an extensive trade-off among various candidate antenna configurations has been performed [2].

The specified coverage/gain/isolation requirements impose an antenna size of about five meter projected diameter.

Active foldable multibeam arrays can provide the required flexibility but they are complex, suffer from scan loss and the required taper for low sidelobe operation implies usually lower overall efficiency. This is also the case for hybrid array-fed reflectors for which, in addition, reflector oversizing is required, unless complex amplitude and phase control is included.

Focus-fed reflectors suffer from excessive spillover or beam cross-over losses unless overlapping feed clusters are used .

Distributed amplification using a Multiport Amplifier can be used but, in the case of the LLM payload, the required matrices would be large and complex. Also, feeding multiple feeds for each beam from the same matrix generally leads to non-uniform amplitude excitation of the amplifiers with a consequent reduction in efficiency.

In order to reduce the above problems, a novel semi-active antenna configuration has been selected for the LLM payload, the "Multimatrix-fed reflector" (ESA patent pending) [1]. In the baseline LLM configuration a deployable reflector of 5x5.6 m projected aperture is used with a feed array of 12 elements in its focus, fed by a multimatrix transmit section. Three feeds are used for each beam, with one feed shared between adjacent beams.

In a Multimatrix-fed reflector antenna, each element in a beam feed cluster is fed from a different, smaller, Butler-like matrix or gen-

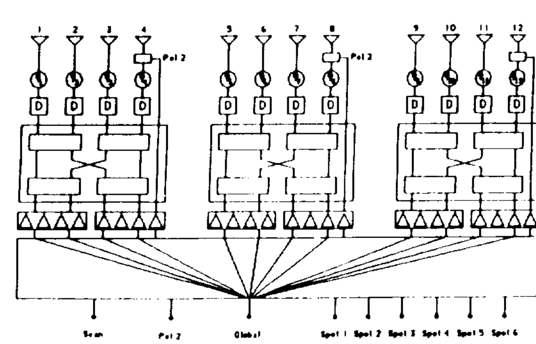

Fig.6: "Multimatrix" TX subsystem

eralised coupler, as shown in Fig-6. The total number of these matrices is equal to the number of feeeds used for each beam. Their order depends on the total number of feeds , and therefore on the total number of required beams. In the LLM payload three 4x4 output matrices are used to feed twelve LHCP feed ports. The RHCP feed ports are feed directly from the TPA section. Each matrix is fed by identical amplifiers. For each beam, the power is directed towards one matrix output port by proper relative phasing of the inputs (0,90,180 and 270 degrees phases are only required). All solid-state amplifiers operate at the same input drive level, with independence of the actual beam-to-beam traffic distribution. This feature maximises the DC to RF conversion efficiency. Power division and phasing for each beam at the amplifier inputs is obtained by a low level beam former (BFN). A fixed BFN is used for the fixed beams, whereas a variable one (5 bit phase control, no amplitude control) is used for the steerable beam and the redundancy beams.

The computed directivity countours for the six fixed spot beams generated by this antenna are presented in Fig-4, showing a crossover of about -3 dB. The steerable beam can also be "scanned" at the nominal or intermediate positions between fixed beams by sharing one or two feeds between adjacent positions. The Eurobeam is generated as shown in Fig-3. A fixed non-uniform phase excitation for the global beam is achieved by adjusting the cable length at the feed level. A compensation for this fixed taper is performed at the low level BFN for the remaining spot beams.

A failure tolerance analysis has been performed for the baseline configuration and the main conclusion is that both the spot and global coverages are seriously degraded by one amplifier failure, and consequently two-for-one cold redundancy has been provided at TPA level. Also a sensitivity analysis versus the BFN errors, the TPA amplitude and phase tracking errors and the hybrids phase and amplitude imbalance has been performed. The results show that although the spot and eurobeam directivity degradation is negligible (assuming realistic hardware implementation), the isolation, and therefore the frequency reuse capability is seriously degraded for aggregate BFN and TPA tracking errors exceeding 0.8 dB and 8 degrees.

L-BAND ANTENNA TECHNOLOGY: In view of the large reflector size required for the LLM payload, an unfurlable reflector is required. Two different reflector technologies have been adressed as candidates [3]:

- Inflatable Space Rigidized reflector
- Foldable radial rib reflector

The Inflatable Space Rigidized reflector is the present baseline. This reflector is manufactured out of prepreg gores precut and joined together. It is composed of three basic elements: A torus used to stabilise and stretch the structure, the reflector/radome membranes to seal the structure and support RF reflecting/transparent surfaces, and the structural interfaces to join the reflector to the spacecraft and to the inflation system. The wall of the reflector consists of a thin fiber reinforced composite lamina, plus a Kapton foil metallised on one side. After inflation in space (duration about 10 minutes) the solar radiation hardens the matrix by a chemical reaction and rigidises the structure from which the nitrogen is evacuated 48 hours after deployment.

Several models of this reflector have been developed and tested including a 6m centered model and a 3.5m offset model. A 10m model is presently under development. A design has been performed for the LLM mission. The reflector is folded for launch in a container providing mechanical packaging and thermal protection. In orbit, after deployment, the reflector is attached to the spacecraft via its container serving as a supporting arm as shown in Fig-7. The total mass of the reflector subsystem including container/arm, pneumatic system and locking mechanism is estimated to be 40.0 Kg.

THE FEED ARRAY: The 12-radiators feed array is mounted on the East spacecraft wall and connected with coaxial cables to the diplexers and the active components. Candidate technologies for the feed array include printed type radiators such as patches or slots, and disk-dipoles or cup-dipoles radiators.

The technology has to provide dual CP capability and passive intermodulation and multipaction free operation up to 40 watts of CW power per feed element.

5 Spacecraft accomodation

The LLM payload is one of the three advanced communication payloads of the ARTEMIS satellite, a pictorial view of which is shown for illustration in Fig-7. The LLM L-band unfurlable reflector is attached by its arm/launch container to the East panel of the spacecraft. The L-band feed array is held in its inclined position from the Earth-facing panel .The Ku-band TX/RX reflector is located on the Earth-facing platform antenna tower. The L and Ku-band power amplifiers are located on the North panel in order to radiate the dissipated power efficiently. The L-band LNAs, L-band diplexers and Butler matrices are distributed between the East and Earth-facing panels, as close as possible to the L-band TX/RX feed array in order to minimise the RF losses. The rest of the equipments is distributed on different panels according to the accomodation constraints imposed by the other payloads.

The mass of the LLM payload is typically 150 Kg and the DC power consumption is 600 Watts. The reliability of the payload has been calculated to be 0.856 for a lifetime of 10 years.

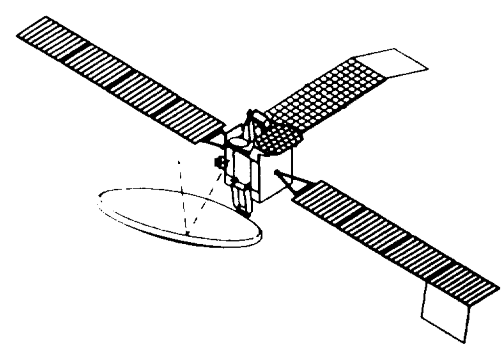

Fig.7: ARTEMIS satellite pictorial view

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